Proceedings Paper:

Hope, David, Dawson, John orcid.org/0000-0003-4537-9977, Marvin, Andy orcid.org/0000-0003-2590-5335 et al. (3 more authors) (2008) Assessing the performance of ZigBee in a reverberant environment using a mode stirred chamber. In: IEEE INTERNATIONAL SYMPOSIUM ON ELECTROMAGNETIC COMPATIBILITY 2008. IEEE , Detroit, USA , pp. 609-614.

https://doi.org/10.1109/ISEMC.2008.4652116

Hope, D.; Dawson, J.; Marvin, A.; Panitz, M.; Christopoulos, C. & Sewell, P. , "Assessing the performance of ZigBee in a reverberant environment using a mode stirred chamber" , Proc. IEEE International Symposium on Electromagnetic Compatibility EMC 2008 , 1-6 , 18--22 Aug. 2008. , DOI: 10.1109/ISEMC.2008.4652116

Assessing the performance of ZigBee in a reverberant environment using a mode stirred chamber

David Hope, John Dawson and Andy Marvin
Department of Electronics
University of York
Heslington, York
YO10 5DD
Email: dch104@york.ac.uk,
jfd1@york.ac.uk
acm4@ohm.york.ac.uk

Mark Panitz, Christos Christopoulos and Philip Sewell
School of Electrical and Electronic Engineering
University Park
Nottingham NG7 2RD
Email: eexmp@nottingham.ac.uk,
Christos.Christopoulos@nottingham.ac.uk,
Phillip.Sewell@nottingham.ac.uk

***Abstract*—The application of ZigBee networks to highly reverberant environments has been investigated using a reverberation chamber. Different Q-factors were set up, by loading the reverberation chamber, and the performance of a COTS ZigBee system was recorded . It has been found that the ZigBee system tested is capable of working in highly reverberant environments and is only seriously limited for a value of Q-factor above 5000, which is greater than that which would typically be encountered outside of a laboratory. The packet error rate (PER) was generally found to be very low for Q-factors between 1000 and 5000, with the possibility a high PER for some combinations of stirrer and antenna positions. With a Q of below 1000 the transceivers were found to work with a PER below 1% regardless of antenna and stirrer positions and the corresponding fading is nearly flat over a data symbol's bandwidth. Radio performance is presented in terms of the packet error rate and this is related to the measured and simulated channel impulse response.**

I. Introduction

ZigBee[1] is a recent wireless standard intended for the deployment of wireless sensor and control applications. ZigBee is built on top of the IEEE 802.15.4 wireless standard [2] that works in the available ISM bands including 915MHz and 2.4GHz. It provides a physical and multiple access layer on top of which higher layers are built. ZigBee is intended for applications including industrial and environmental monitoring and some home applications such as wireless light switches or heating systems. Beyond the standard uses it is possible to envisage applications in ships, cars and aircraft where wireless sensors would be useful. For example an aircraft may have a number of metallic avionics bays or a ship a number of sealed metallic bays. Such environments provide an EMC environment more complex than that in a typical home, office or outdoors as they are highly reverberant with significant energy storage and high delay spread. Therefore a number of experiments have been designed and carried out in order to check that the ZigBee standard will work in such environments and to ascertain the limits on the operational conditions. The aim of the work is to assess whether ZigBee systems will operate reliably in a reverberant environment where movement (e.g. flexing of the structure) may occur, such as a vehicle in motion

II. The IEEE 802.15.4 Standard

Before describing the work undertaken a brief overview of the 802.15.4 standard is presented in order that the following analysis can be understood.

A. Physical Layer

The physical layer data rate for 802.15.4 (for the transmitted bit stream including all protocol overheads) is specified as 256 kbps for the 2.4 GHz band. A direct sequence spread spectrum (DSSS) based modulation is applied to the bit stream and is followed by OQPSK modulation with half sine pulse shaping This is also known as a form of continuous phase frequency shift keying (FSK) called minimum shift keying (MSK). It can be understood in terms of a phase modulation where the in-phase (I) and quadrature (Q) channel bit-streams are offset from one another by half a bit period meaning that maximum phase transitions are 90 degrees. The pulse shaping ensures a constant envelope so the modulation can be visualised as the phasor rotating 90 degrees between each symbol. The probability of error for this scheme in additive, Gaussian white noise is given by Peebles [3] as:

$$\frac{1}{2}\,erfc\,[\sqrt{\epsilon}] \tag{1}$$

where

$$\epsilon = \frac{A^2 T_b}{2N_0} \tag{2}$$

where N_0 is the one sided noise spectral density, A is the received signal amplitude, T_b is bit period and $erfc()$ is the complementary error function. It is expected that error rates in our experiments will differ from this where there is a high Q-factor and the inter-symbol interference due to the long

978-1-4244-1699-8/08/$25.00 ©2008 IEEE

reverberation time and that Rayleigh/Ricean signal amplitude statistics will become dominant. DSSS with a spreading factor of 8 is used to improve performance under multi-path fading. It is implemented by taking bits of the input data stream, and using them to select one of 16, 32-chip spreading codes. The chip-sequence is then split into two sequences each made up of alternate chips from the original sequence and when transmitted the second sequence is delayed by half a chip period relative to the first. Both sequences then have their chips shaped into half sine forms and the two sequences are sent to the I and Q modulation paths respectively. The chip rate after spreading is 2 Mchip/s . When demodulating one can look at symbols rather than chips or bits and the symbol rate is 1/4 of the bit rate (or consists of 32 chips) and so has rate 64ksps. The equivalent symbol time is 15.63μs and the significance of this is that if the delay is of the same order as this then there is a high probability of incorrectly interpreting a symbol. In fact it is shown in Rappaport [4] that for a digital modulation scheme, where the symbol period is T_s and the RMS delay spread is σ, once σ/T_s becomes greater than 0.2 a link can become unusable. Packet error rates will differ from the rate predicted by the bit-error-rate (BER) given in Equation 1. First this result only applies to the chip-error-rate for this scheme. By using direct sequence spread spectrum with a chip to bit ratio of 8, a processing gain[4] of 9dB is added to the signal to noise ratio. Secondly a packet error can be produced by a single bit-error or multiple bit errors within a packet. The specification for IEEE 802.15.4 specifies that a physical layer data unit, i.e. a ZigBee packet can have a maximum length of 127 octets or 1016 bits. Thus the packet error rate could be expected to be higher and dependent on the sum:

$$PER = \sum_{i=1}^{N} P_b^i \left(1 - P_b\right)^{N-i} \tag{3}$$

or alternatively as

$$PER = 1 - \left(1 - P_b\right)^N \tag{4}$$

where P_b is the probability of bit error (given by Equation 1 with the spreading gain included) and N is the number of bits in a packet. These formulas can be plotted giving the standard BER curves and suggest a predictable rate of errors dependent on the signal to noise ratio. It is unlikely this will be the case in a highly reverberant environment where delay spread and fading may dominate the performance so measurements and simulations are needed to determine the dominant cause of error in such an environment.

B. Selected COTS test system

In order to assess performance a commercial off the shelf system (COTS) was purchased which was the Jennic 5139 series based development kit. Only one system was purchased but it should be noted that performance may vary dependent on the particular implementation of the receiver system. Demodulation for this system is done non-coherently using correlation, i.e. the demodulation does not require an in-phase carrier signal to be generated. It uses a low IF architecture in the radio receiver. Sensitivity is specified at -95.5dBm which is better than the -85dBm required by the IEEE 802.15.4 specification [2]. This means BER will be lower for a given noise power than a system that meets the standard exactly.

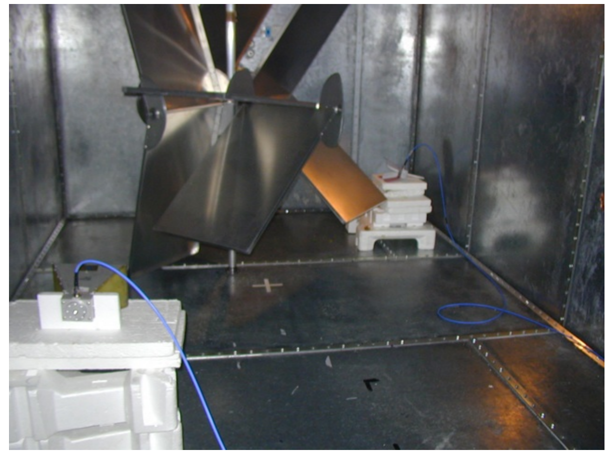

Fig. 1. The University of York reverberation chamber showing the stirrer and a setup with two horn antennas

C. Aim of measurements

There were three aims to the measurements that were taken:

- Understand how ZigBee performs in a range of reverberant environments
- Understand how movement in the environment affects performance
- Be able to relate the impulse response of the environment to performance

D. Measurement set up

1) Mode stirrer chamber: A mode stirred or reverberation chamber is a resonant cavity operated in a frequency range where many resonant modes are excited, with a mechanical device for 'stirring' the field inside the chamber and an example is shown in figure 1. Reverberation chambers have been found useful for communications measurements because they can replicate a Rayleigh or Ricean fading environment which changes as the stirred is moved [5]. It may be used to emulate multi-path propagation effects as the many reflections over a short distance can cause a time delay such that there is phase shift that is high relative to the wavelength, just as a few reflections over a long distance can. The dimensions of the larger chamber used are 4.7x3.0x2.37m. There were no additional noise sources and the receiver noise figure is given by the manufacturers as approximately 10dB at room temperature. Where reference is given to the smaller chamber this has dimensions of 0.6x0.7x0.8m. In order to control the energy in the chamber and therefore the Q-factor and delay spread, AN79 absorber was added in varying amounts.

2) Obtaining the channel response: An Agilent E5071B network analyser was used to measure the frequency response of a channel between the antenna terminals in the form of the S21 network parameter. The IEEE 802.15.4 standard specifies a number of channels over an 85MHz bandwidth. The channels themselves are spaced at 5MHz intervals and partially overlap. Measurements were taken over a bandwidth of 84MHz which covers the majority of the ZigBee channels, and was picked for numerical convenience when doing post processing. Measurements were taken with a 0.06MHz step size from 2.4GHz to 2.484GHz resulting in a total of 1401 data points. Each measurement over the frequency range was taken with the stirrer static at a particular position. A number of these measurements were taken at different stirrer positions in order to obtain channel statistics, with the number of measurements depending on the particular experiment.

In order to determine the time response of the channel the data was first padded with zeros up to 2.4GHz in 0.6MHz steps. A discrete Fourier transform was then applied to produce the channel impulse response.

III. Measurements

The channel impulse response and ZigBee performance were both measured in the reverberation chambers with the stirrer static, in a number of different positions and with the stirrer in motion. Radio absorptive material was introduced into the chambers to control the Q-factor.

A. Channel response with variation in Q

An example of a time and frequency response of the coupling (S21) between the antenna terminals in the large reverberation chamber is presented in Figure 2 . As expected it was found that decay time was reduced and the frequency response of the channel became flatter over a larger bandwidth as the amount of absorber in the chamber was increased. For a quantitative measure of the channel time response, mean excess delay and RMS delay spread were calculated for each value of Q and are presented in tables I and II, with the former coming from the large chamber and the latter from the small chamber. In order to calculate chamber Q the following formula was used [6]:

$$Q = \frac{16\pi^2 V \langle P_{rec} \rangle}{\eta_{Tx}\eta_{Rx}\lambda^3 \langle P_{in} \rangle} \tag{5}$$

where instead of the received and transmitted powers we use the square of the network parameter S21 which provides this ratio. Mean excess delay and delay spread were calculated according to the definitions given in Rappaport [4] . The mean delay spread is:

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2}$$

and the RMS delay spread is

$$\tau_{RMS} = \sqrt{\bar{\tau^2} - (\bar{\tau})^2}$$

TABLE I

Delay spread and Q in York's large reverberation chamber

Absorber	Q (approx)	Mean Excess Delay (μs)	RMS Delay Spread (μs)
None	28000	15.5	14.9
0.25 pieces	12600	6.75	6.65
0.5 piece	10000	4.65	4.80
0.75 pieces	7300	4.2	3.9
1.25 pieces	5500	3.00	2.95
2.25 pieces	3900	2.00	1.95

TABLE II

Delay spread and Q in York's small reverberation chamber

Absorber	Q (approx)	Mean Excess Delay (μs)	RMS Delay Spread (μs)
None	900	0.61	0.53
0.5 pieces	550	0.33	0.30
1 piece	370	0.26	0.24

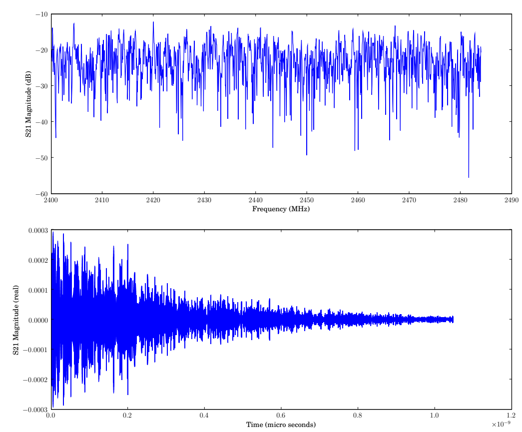

Fig. 2. Time and frequency response for transmission (S21) between two ZigBee quarter wave antennas in York's main reverberation chamber from 2.4GHz to 2.484GHz for the empty chamber (no absorber)

where

$$\bar{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2}$$

where a_k is the amplitude of the time domain channel impulse response at time τ_k.

Given the need for delay spread to be within 1/5 of the symbol time this would suggest that a high error rate will occur up to the point where delay spread is less than 3 μs for the ZigBee system and therefore Q should be kept under 5000 in any environment in which it might be used. As enclosures in vehicles, (e.g. avionics bays) are typically of a size closer to the small chamber than the large chamber, and given that the totally unloaded Q in the small chamber is less than 1000

TABLE III
PACKET ERROR RATES (PER) FOR JENNIC ZIGBEE KIT IN YORK'S MAIN MODE STIRRED CHAMBER AVERAGED OVER TEN STIRRER POSITIONS

Absorber	Q (approx)	Average PER	No. of positions out of 10 PER $< 1\%$
None	28000	100%	0
0.25 pieces	12600	58%	3
0.5 piece	10000	50%	3
0.75 pieces	7300	42%	4
1.25 pieces	5500	22%	7
2.25 pieces	3900	11%	9

[7], then theoretically this should not present any issues in a practical usage.

B. Performance of ZigBee with varying Q-factor

The packet Error Rate, as obtained using the Jennic 5139 ZigBee development kit's Production Test API was recorded for each of the values of Q used for the channel measurements.

TABLE IV
PACKET ERROR RATES (PER) FOR JENNIC ZIGBEE KIT IN YORK'S SMALL MODE STIRRED CHAMBER

Absorber	Q (approx)	PER
None	900	0.6%
1 piece AN79	550	0.1%
3 pieces AN79	370	0.8%

Tables III and IV present the results for variation of PER with Q-factor. For the large chamber these numbers are an average over 10 stirrer positions for a particular Q-factor/quantity of absorber. There is a stirrer rotation of 3 degrees between each position. This was selected because there is no correlation between positions with this separation ensuring independent samples. In the case of the small chamber the stirrer was moving continuously at a slow rate as a stepper motor was not available . It can be seen from these tables that ZigBee generally functions reliably when the Q-factor is less than 5000 and possibly at higher values but it won't work reliably when the Q-factor is 10,000 and above. It is assumed that any packet error rate above 1% is likely to cause significant performance degradation in a packet based system although simulation or tests of a complete and specific system would be needed to get a precise number. Even in the case of a Q of 3900 there was one of the ten positions where the error rate is greater than 1% (in fact this was 100%). Although for most stirrer positions the link will work , if the stirrer moves into one of the ten positions with 100% PER the link would fail. Therefore for critical applications it is important to know when there will be no failure and this scenario did not occur until the measurements of Q below 1000. Q-factors as high as 5000 and above are unlikely to be encountered in most applications. It has already been stated that in a cavity of similar size to the small chamber the Q is below 1000 and allowing for leakage and absorption it will be lower still. There may be

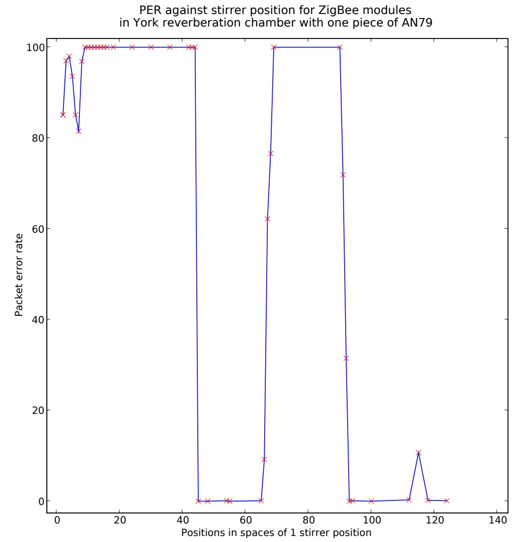

Fig. 3. Performance of ZigBee in the York reverberation chamber for a Q of 7000 at different stirrer steps (a step is 0.056 degrees, and corresponds to a movement of about 1 mm at the periphery of the stirrer)

some scenarios where high Qs are encountered however, for example, in sealed cavities, such as a fuel tank in an aircraft or car or a large cavity in a ship designed to be waterproof. The Qs in such places are unknown but should be confirmed before using ZigBee without any additional absorber.

We may relate the performance in the different Q-factors back to the ZigBee symbol time given earlier. At the maximum Q of 28000 the RMS delay spread was 15 μs and the ZigBee symbol time is approximately equal to this. Therefore a large amount of inter-symbol interference is likely and this can also be derived by looking at the frequency response in figure 2 where there is significant frequency selective fading over a 5 MHz range which is the channel width in ZigBee. For a Q of 7000 the RMS delay spread was found to be 3.9 μs which is approximately 1/4 of the symbol time. In such conditions a link may or may not work but at this level there will be some inter-symbol interference and error free operation is unlikely. By the point where the delay spread is 1/10th the symbol time, the system would be expected to work reliably This is nearly the case for a Q of 4000 although certain stirrer positions still cause packet errors.

Measurements were taken in an environment with no added noise, only the inherent thermal and receiver noise were present. It was calculated that the equivalent noise temperature on the input was approximately 2900K or the noise power was 97dBm assuming a 5MHz bandwidth (in fact it will be a little high than this). Signal power was measured on a spectrum analyser as being -20dBm providing a signal to noise ratio of 77dBs. Applying this to equation 1 gives an effectively 0% chip error rate and thus BER and PER indicating that errors are due to fading (likely frequency selective given the low noise level), not Gaussian noise in the chamber. Approaching

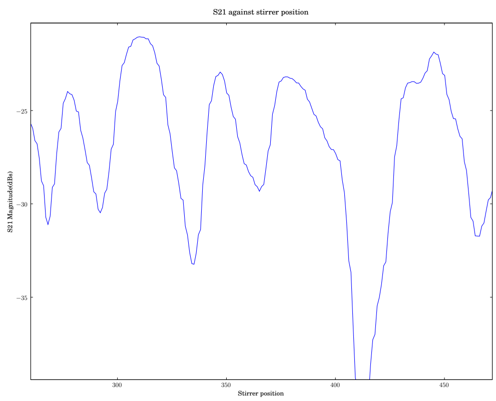

Fig. 4. Variation of S21 magnitude in dBs over stirrer steps in the York reverberation chamber at a Q of 7000 (a step is 0.056 degrees, and corresponds to a movement of about 1 mm at the periphery of the stirrer)

this issue from an different direction one can look at the transmit power of the ZigBee modules which are specified as being 0.5dBm. From figure 4, showing variation of the channel response/attenuation with stirrer position one can see the level of attenuation is generally higher than -40dB. Therefore the power is typically greater than -39.5dB. Earlier it was stated that the sensitivity of ZigBee is -95dBm for 1%PER i.e. this is the minimum signal level that can be processed if there is no external noise. Additional external noise will reduce this but it is far from the -39.5dB again suggesting symbol errors are not caused by a low signal to noise ratio. Further work is needed and is being carried out to find out how performance in the different Qs varies for different noise levels.

C. Performance variation with stirrer position

As previously explained stirrer movement can be likened to physical deformation of the structure (e.g. vibration and flexing), or movement of the receiving or transmitting antenna and additional information may be ascertained as to the behaviour of the system by looking at BER variation with stirrer position. For a chamber with a Q-factor of 7000 the data in Figure 3 suggest that there is total packet loss at approximately 50% of positions and that the nature of the system is that it either works or it does not work. This was found in most of the tests conducted where PER was normally 0% or 100% with intermediate values less frequent. This indicates that the errors are not due to a slow fading where the signal to noise ratio is modulated from one stirrer position to the next. Rather the cause of the error may be the inter-symbol interference caused by the high levels of reverberation which is leading to the symbols being incorrectly detected. Alternatively it could be the failure to synchronise at the start of the packet (by the preamble) as required to correctly sample and thus decode the symbol. The data in the packet being sent each time is the same in the test with the exception of the packet number. Furthermore the preamble is always be the same which is necessary for the system to work. Therefore it is hard to say whether the cause is the initial synchronisation or the inter-symbol interference but regardless it appears to be an issue of high delay spreads.

D. Computational Modelling

Alongside the measurement programme computational modelling has been carried out. It will not be possible to test a ZigBee system in every possible environment it is to be used in and it may be that once something is built whether the radio works or not it is too late to make any changes. Therefore being able to simulate an environment and make predictions as to whether or not a wireless system is likely to work is important, for example if the model reveals that delay spread or Q-factor could be too high then absorber could be added. Simply putting equipment in and seeing if it works may not be sufficient as shown in figure 3. Therefore there has been some work into the simulation of reverberant environments using full field TLM methods which has led to the creation of a model of York's smaller reverberation chamber that proves a close match. An alternative, simpler model simulated the environments by using a number of LCR circuit components in parallel that can model the different modes. When the measured frequency response is studied it consists of a number of peaks each with their own Q. Therefore each LCR section can represent a different peak recreating the frequency response of the chamber. Such models allow ZigBee performance to be modelled for reasonably arbitrary geometries where the important characteristics are the amount of absorption, defining the Q and mode density. The output of simulations is a channel transfer function like the measured S21 parameter. With this function predictions about performance can be made by looking at the delay spread, although if Q is known then delay spread may be estimated from it or if greater accuracy is required the model or its statistics may be incorporated into a full communications simulation. Results are reported in [8] for EMC Europe 2008 (unpublished).

E. Performance of ZigBee with varying speed

Some brief measurements were carried out to see the effect of a time varying channel on the PER. This was done by varying York's main chamber's stirrer speed for a set value of Q which was selected as 7000 to ensure there were enough errors to see some variation. Figure 5 shows that performance was significantly better for lower stirrer speeds. Increasing speed increased packet error rate in a non linear way converging to a particular level. This reinforces an initial assumption that there is no evidence of Doppler shift or fast fading relative to the symbol time. If this was the problem then it would be expected that the fading got worse as speed went up until a point of no packets getting through. What might have been expected is that the PER with a moving stirrer was equal to the average PER over many stirrer positions but this is not the case. It may be that the extra moving of the channel, even when the movement is very small is causing a movement

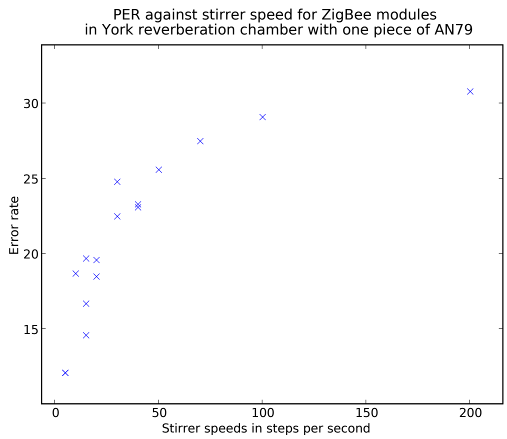

Fig. 5. Measurement of percentage packet error rate for Jennic ZigBee development kit at different stirrer speeds. The chamber has a Q of approximately 7000. For reference 50 corresponds to 2.8 degrees per second

of the very high order modes which results in extra intersymbol interference not over a symbol period but over a packet (i.e. over many symbols) where at a single position with no variation over a symbol, this couldn't have occurred. Further research is needed to better understand what is happening.

IV. Conclusion

Measurements have been made of the performance of ZigBee in static and time varying reverberant environments using mode stirrer chambers. It has been found that in most real world situations where Q-factor is below 1000 transmission will be possible but when the Q is increased to beyond 1000 or the delay spread goes beyond a few microseconds it will no longer be guaranteed to function correctly. Generally the system will be reliable up to a Q-factor of 5000 but there may be positions of the antennae where the link fails at this level of Q-factor. All experiments were done without any external noise sources and results may change with additional noise. However in these experiments, in high Q environments frequency selective fading was found to be the main cause of errors. There is not a simple relationship between performance and Q-factor, for example by PER being proportional to Q, although average PER does fall with Q when the average is over a number of stirrer positions. Unlike in the Gaussian noise situation there is not a gradual falling off in performance but rather there is a steep cut off after which the system fails to operate correctly. In many cases PER was either 0% or 100% and so it is important that in any installation Q is sufficiently low there is no chance of moving into a position with error rate 100%. Simulation techniques have been developed to match the measurements and these may be done in order to predict delay spreads, indicating environments where extra absorbing material might be needed.

Early experiments have shown that movement of the stirrer has the effect of increasing the error rate and that this converges to a maximum value but further work is needed in this area.

Acknowledgement

The work presented here was funded by BAE and the EPRSC under the Flaviir programme.

References

[1] "Zigbee specification," http://www.zigbee.org/en/index.asp, Zigbee Alliance.

[2] "IEEE Std 802.15.4-2003," http://www.ieee802.org/15/pub/TG4.html, IEEE.

[3] J. P. Z. Peebles, *Digital Communications Systems*. Prentice-Hall, 1987, iSBN 0-13-211962-5 025.

[4] T. S. Rappaport, *Wireless Communications Principles and Practice*. Prentice Hall, 1996, iSBN 0-13-042232-0.

[5] C. L. Holloway, D. A. Hill, J. M. Ladbury, P. F. Wilson, G. Koepke, , and J. Coder, "On the use of reverberation chambers to simulate a rician radio environment for the testing of wireless devices," *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*, vol. 54, no. 11, pp. 447 – 473, 2006.

[6] D. A. Hill, "NIST technical note 1506, electromagnetic theory of reverberation chambers," NIST, Tech. Rep., December 1998.

[7] D. M. Johnson, M. O. Hatfield, M. B. SLocum, T. A. Loughry, A. R. Ondrejka, R. T. Johnk, and G. J. Freyer, "Phase II demonstration test of the electromagnetic reverberation characteristics of a large transport aircraft," Naval Surface Warefare Center, Dahlgren, Virginia, USA, Tech. Rep. NWSCDD/TR-97/84, September 1997.

[8] M. Panitz, C. Christopoulos, P. Sewell, D. Hope, J. Dawson, and A. Marvin, "Modelling wireless communication in highly-multipath low-loss environments," *EMC Europe*, 2008.